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Mass dependence of π^0-production in heavy ion collisions at 1 A GeV

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The production of neutral pions has been studied in the reactions $^{40}Ar+{}^{nat}Ca$, $^{86}Kr+{}^{nat}Zr$ and $^{197}Au+{}^{197}Au$ at 1 A GeV. For high energy pions emitted from the heavier systems a steeper than linear rise of the pion multiplicity with the centrality of the reaction is observed, indicating a pion production process other than binary nucleon–nucleon collisions. At low transverse momenta an enhancement of the π^0-multiplicity increasing with the mass of the collision system is found. Systematic discrepancies between the experimental results and recent BUU, QMD and Cascade calculations are discussed.

Theoretical descriptions of relativistic heavy ion collisions [1–3] indicate that at bombarding energies of the order of 1 A GeV nuclear matter can be compressed as in stellar processes to 2–3 times the normal density. Simultaneously some 10% of the nucleons are excited to baryon resonances like $\Delta(1232)$ and higher states. Relativistic heavy ion collisions appear to provide the only access to the properties of such compressed and intrinsically excited hadronic matter under controlled conditions in the laboratory. Experimentally, two approaches have been pursued in these investigations. Emission patterns of nucleons and complex fragment formation in central heavy ion collisions have been measured and studied in a global analysis. Phenomena such as *sideward flow* [4], *squeeze-out* [5] of baryons and an explosion-like expansion of the collision zone [6] have been observed, providing information on the dynamics of the heavy ion reaction. A complementary approach is to investigate the production of particles [7] not present in the entrance channel, such as photons, mesons and antiprotons. These particles have been studied with respect to their abundancies, momentum spectra and their distribution relative to the reaction plane [8,9].

So far particle production in heavy ion reactions

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has mainly focussed on charged pions [7,10–15]. Inclusive production cross sections show a linear rise with the number of participant nucleons which is explained by pion production via $\Delta(1232)$ excitation in binary nucleon–nucleon collisions [10,11]. Pion spectra exhibit a steep fall as a function of the transverse momentum p_t with an increasing concavity for higher bombarding energies and larger masses of the collision system [12,15]. Various possible explanations for the concave shape of pion spectra like collective flow, directly produced pions or higher resonance contributions have been suggested [15]. Presently there is no convincing proof for any of these interpretations. The excitation of higher baryon resonances in heavy ion collisions has, however, been demonstrated by the observation of η-mesons [16] which arise predominantly from the decay of the $S_{11}(1535)$ resonance. Consequently, low lying baryon resonances as N(1440) and N(1520) are very likely also excited. A more refined analysis is required to establish their contributions to the pion spectra. Recent BUU-simulations [17] suggest that higher baryon resonances are populated in multi-step processes which become more important in very heavy collision systems. A characteristic feature would be a deviation from a linear dependence of the π-multiplicity on the number of participant nucleons for high transverse momenta.

Contrary to charged pions which can only be detected above a certain p_t-threshold the measurement of neutral mesons offers the advantage that they can be detected via their two-photon decay down to transverse momentum $p_t = 0$ MeV/c, moreover their spectra are not distorted by Coulomb effects. A large body of π^0-data exists only at bombarding energies below the production threshold in free nucleon–nucleon collisions (280 MeV) [18,19]. This has motivated a series of experiments at higher energies performed at the new heavy ion synchrotron SIS at Gesellschaft für Schwerionenforschung in Darmstadt. Part of this work has recently been published [16,8].

In the present paper we report on a first systematic study of π^0-production in three approximately mass-symmetric systems of different total mass (^{40}Ar+^{nat}Ca, ^{86}Kr+^{nat}Zr and ^{197}Au+^{197}Au) at the same incident energy of 1 A GeV. Pion production cross sections and transverse momentum spectra were determined. In addition to earlier charged pion measurements the mass dependence of neutral pion production was studied for the first time for different bins in transverse momentum. Such an analysis offers the opportunity to distinguish between various production mechanisms for pions of different energy.

The beam intensity was 10^5–10^6 particles per spill with a duty factor of $\approx$ (30–40)%. The targets corresponded to reaction probabilities of 3.9% (Ar+Ca) and 0.45% for the two heavier systems, respectively. The π^0-decay photons were detected with the photon spectrometer TAPS (Two Arm Photon Spectrometer) [20]. Charged particles escaping from the reaction zone at laboratory angles between 1° and 30° with respect to the beam were observed in the Forward Wall (FOPI) of the 4π detector system [21]. Only the total charged particle multiplicity measured in the polar angle range from 7°–30° has been used in the present analysis.

Table 1
Geometrical setups and detection efficiencies of the TAPS detector system in the different experiments. In the Au+Au experiment two different detector setups have been used in order to cover a larger kinematical range. Φ denotes the angle of the TAPS blocks with respect to the horizontal plane. d is the distance between the blocks and the target. The angle of the TAPS towers with respect to the beamline (Θ) has been adjusted to ±52.0° in all experiments. $\epsilon_{\pi^0}^{geo}$ is the geometrical efficiency for pions emitted from an isotropic thermal source with temperatures T (T_1 and T_2 for the heavier systems) from table 2 while ϵ_{π^0} includes photon and π^0-reconstruction efficiencies. The error in the detection efficiencies arising from an uncertainty in the temperature parameters amounts to less than 5%.

Experiment	d (cm)	Φ (deg.)	$\epsilon_{\pi^0}^{geo}$	ϵ_{π^0}
^{40}Ar+^{nat}Ca	120	±12.1	1.8×10^{-3}	3.5×10^{-4}
^{86}Kr+^{nat}Zr	160	±16.0/ ± 9.5	7.4×10^{-4}	2.9×10^{-4}
^{197}Au+^{197}Au (A)	200	±23.0	4.4×10^{-4}	2.2×10^{-4}
^{197}Au+^{197}Au (B)	200	± 7.3	2.5×10^{-4}	1.2×10^{-4}

TAPS is a modular detector system consisting of 256 BaF_2 detectors arranged in 4 identical blocks with individual Charged Particle Veto detectors (CPV) mounted in front of each module. The blocks were arranged in two movable towers positioned symmetrically with respect to the beam direction to detect pions emitted in the mid-rapidity region ($y_{lab} = 0.52$–0.84). Within each tower the blocks were positioned symmetrically with respect to the horizontal plane containing the beam axis. All geometrical settings are listed in table 1. The main trigger required two coincident photon candidates in TAPS corresponding to a minimum bias condition for pion detection.

Charged particles were discriminated by requiring an anti-coincidence between a BaF_2- and the corresponding CPV-module. Photons and hadrons were separated via pulse-shape and time-of-flight analysis. A linear energy calibration of the BaF_2-modules was based on the energy-loss signals deposited by cosmic muons ($\approx$38 MeV). Photon energies deposited in adjacent modules were summed in order to reconstruct the electromagnetic shower. The point of impact was determined from the shower distribution using logarithmic energy weights [22].

Neutral pions were identified via their invariant mass deduced from the measured photon energies and angles with a resolution in $\Delta m(\mathrm{FWHM})/m \approx 15\%$. The combinatorial background from uncorrelated photon pairs was obtained by event mixing. This background, which can be determined with high statistical accuracy, was subtracted from the invariant mass and pion momentum distributions. In order to correct the measured distributions the acceptance of TAPS was simulated as a function of the pion transverse momentum p_t and the lab rapidity y using the detector-response package GEANT3 [23]. The resulting efficiencies are listed in table 1. The experimental transverse momentum resolution amounts to $\Delta p_t(\mathrm{FWHM})/p_t \approx (7$–$16)\%$ depending on the value of p_t.

All measured cross sections and multiplicities for neutral pions emitted at mid-rapidity are listed in table 2. In addition the results of an extrapolation to the full solid angle assuming an isotropic thermal source with the measured slope parameters (see below) are given. The inclusive pion cross section (see table 2) can be factorized [2]

$$\sigma_{\pi^0} = \sigma_R M_{\pi^0} = \sigma_R \langle A_{\mathrm{part}} \rangle_b P_{\pi^0} \qquad (1)$$

where σ_R denotes the reaction cross section. M_{π^0} defines the measured pion multiplicity per reaction, P_{π^0} is the pion production probability per participant nucleon and $\langle A_{\mathrm{part}} \rangle_b$ is the number of participant nucleons averaged over the impact parameter b taken from a geometrical model [24]. The derived values for P_{π^0} are $(3.0 \pm 0.3)\%$ for Ar+Ca, $(4.6 \pm 0.7)\%$ for Kr+Zr and $(3.7 \pm 0.4)\%$ for Au+Au. Although an additional systematic error of 30% has to be taken into account in the direct comparison of the three target–projectile combinations the pion production probability seems to be somewhat higher in the heavier systems. Because of pion absorption one would naively expect the opposite trend, i.e. P_{π^0} to decrease with increasing mass. The experimental result indicates that pion absorption is compensated or even overcompensated in the heavy systems by additional production mechanisms discussed below in an analysis of the differential pion multiplicity. Harris et al. [10,11] observed a linear increase of the π^- multiplicity with the number of participant nucleons within a given collision system corresponding to a constant pion emission probability

Table 2
Cross section σ_{π^0} and multiplicity per reaction M_{π^0} for neutral pions emitted at mid-rapidity ($y_{lab} = 0.52$–0.84). $\langle p_t \rangle$ and the fitted temperature parameters (T for one and T_1,T_2 for two-component fits) refer to the pion transverse momentum spectra. The results of an extrapolation to the full solid angle taking the experimental temperatures into account are also given.

System	In rapidity range Δy						Extrapolation to 4π	
	$\sigma_{\pi^0}^{\Delta y}$ (b)	$M_{\pi^0}^{\Delta y}$	$\langle p_t \rangle$ (MeV/c)	T (MeV)	T_1 (MeV)	T_2 (MeV)	σ_{π^0} (b)	M_{π^0}
Ar+Ca	0.31 ± 0.03	0.12 ± 0.01	198 ± 9	64 ± 1	-	-	1.5 ± 0.2	0.6 ± 0.1
Kr+Zr	2.1 ± 0.3	0.43 ± 0.06	183 ± 7	60 ± 1	48 ± 8	76 ± 10	9.4 ± 1.3	1.9 ± 0.3
Au+Au	6.5 ± 0.7	0.83 ± 0.08	180 ± 7	60 ± 3	38 ± 4	78 ± 4	28.0 ± 3.0	3.7 ± 0.4

per participant nucleon. Stock [7] interpreted this observation as evidence for a chemical equilibrium between Δ's and nucleons established via the ΔN ⇔ NN channel. The present result on neutral pions obtained in a comparison of different systems is consistent with these earlier observations and interpretation.

Fig. 1 shows the measured π^0-transverse momentum p_t distributions for pions emitted at mid-rapidity. The average transverse momentum decreases systematically with the mass of the collision system (see table 2). In case of the lightest system (Ar+Ca) the measured shape can be well described (dashed curve) with the distribution

$$\frac{1}{p_t}\frac{\mathrm{d}\sigma}{\mathrm{d}p_t} \propto m_t \exp(-m_t/T), \qquad (2)$$

where $m_t = \sqrt{p_t^2 + m_{\pi^0}^2}$ and T is a fit parameter [25]. Only at high p_t a slight enhancement is noticeable. In contrast, the reproduction of the spectra of the heavier systems (Kr+Zr and Au+Au) requires the assumption of two components with temperature parameters T_1 and T_2 (solid curves). The

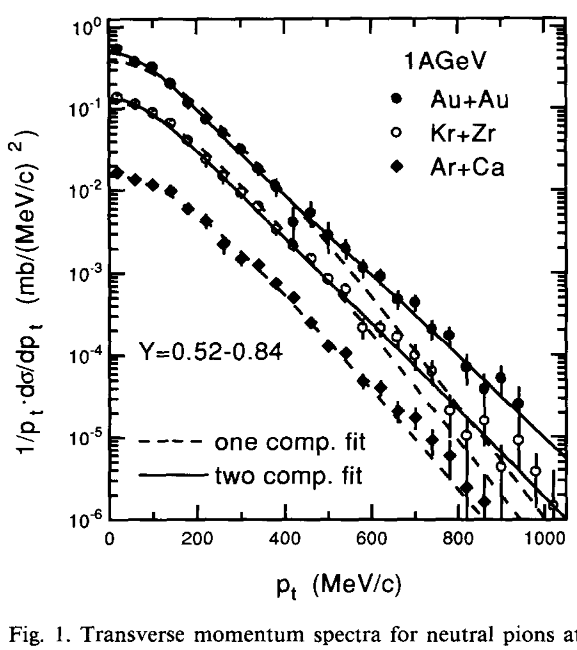

Fig. 1. Transverse momentum spectra for neutral pions at y = 0.52–0.84 measured for three systems with different total mass at a bombarding energy of 1 A GeV. The dashed and solid lines represent one- and two-component fits to the spectra, respectively, using eq. (2) (parameters see table 2).

difference in the temperature parameters increases with the total mass of the collision system, reflecting an increasing concavity of the spectral shape. All fit results are summarized in table 2.

In an attempt to identify possible contributions of higher baryon resonances to the spectra the differential pion multiplicity $\mathrm{d}M_\pi/\mathrm{d}M_{\mathrm{cha}}$ has been determined for different bins in p_t (a–d) as a function of the charged-particle multiplicity M_{cha} observed in the FW. This dependence has been parametrized as $\mathrm{d}M_{\pi^0}/\mathrm{d}M_{\mathrm{cha}} \sim M_{\mathrm{cha}}^{\alpha}$ (fig. 2). Hereby, M_{cha} is taken as proportional to the number of participant nucleons A_{part} determined by the centrality of the reaction [6]. If pion production occurs in independent binary nucleon–nucleon collisions a linear dependence on the number of participant nucleons is expected ($\alpha = 1$). In the lightest system (Ar+Ca) the exponent α does not depend on the pion momentum. In contrast to [10,11], we observe a steeper increase of the pion multiplicity for high energetic pions ($p_t >$ 600 MeV/c) in the heavier systems. This behaviour indicates a different production process and might be related to higher-order (=multi-step) processes such as multiple collisions leading to the population of heavier resonances. Such processes may involve the excitation of a Δ-resonance in a first nucleon–nucleon collision followed by a collision of the Δ with a third nucleon in which the Δ-mass is exploited for the excitation of a higher lying resonance. Thereby the energy of 3 nucleons can be pooled to populate a heavier baryon resonance which subsequently decays into pions of higher energy, leading to the observed enhancement in pion spectra at high momenta. BUU calculations [26] also indicate that the high p_t part of the pion momentum spectra is enhanced by an increasing contribution of pions from N(1440) decays. The probability for two-step processes is proportional to the third power of the baryon density. Their observation is thus a signature for the high compression reached in heavy ion collisions. The multi-step reaction mechanism is expected to be more favored in heavier systems where the high baryon density is maintained over a longer time period [17]

The overall change of the spectral shape for the investigated systems is also reflected by the ratio of the transverse momentum distributions of the two heavier systems divided by that of the system Ar+Ca (fig. 3). Here, an enhancement at low *and* high transverse mo-

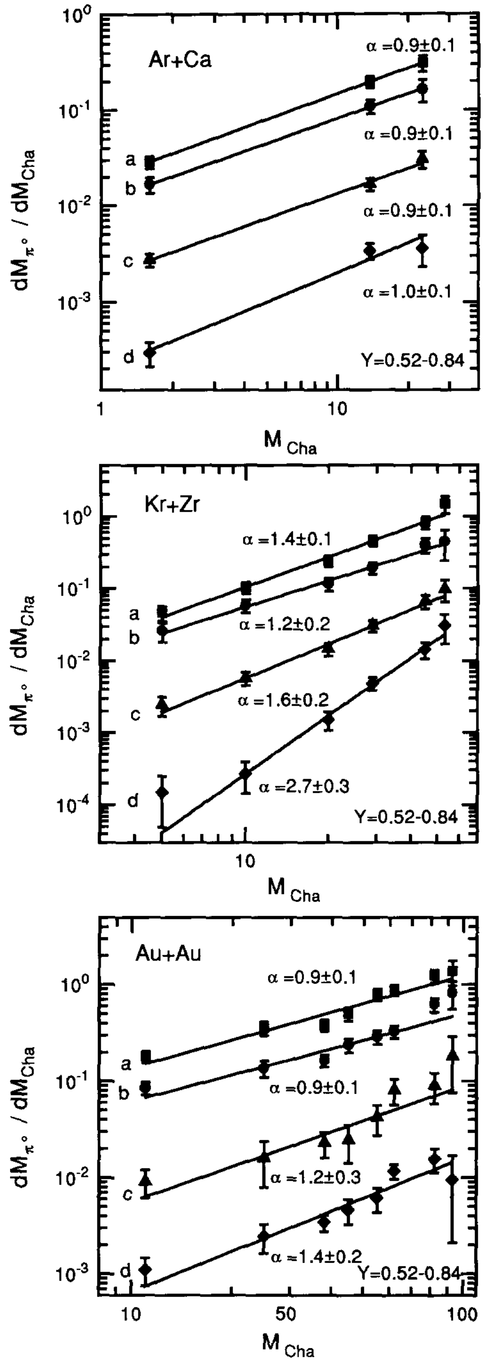

Fig. 2. Differential π^0 multiplicity per reaction for the three systems as a function of the charged particle multiplicity in the FW for different bins in p_t: 0–200 MeV/c (a), 200–400 MeV/c (b), 400–600 MeV/c (c) and 600–800 MeV/c (d).

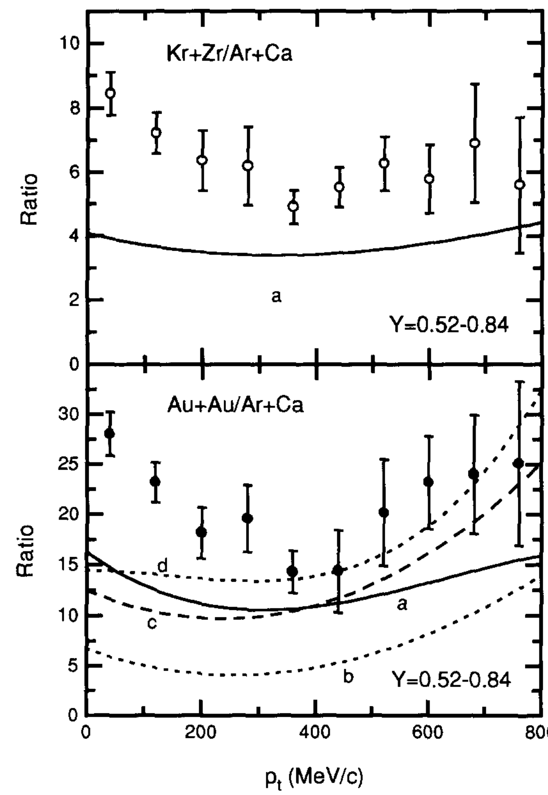

Fig. 3. Ratio of the measured transverse momentum spectra of the two heavy systems relative to the spectrum of the system Ar+Ca. For comparison the results of various theoretical calculations are shown (a: BUU [26], b: IQMD [27], c: RQMD [28], d: Cascade based on QGSM [29]).

menta is observed. For comparison, the results of various theoretical calculations are included, made available to us for the relevant rapidity ranges. Obviously, the mass dependence cannot be reproduced by any of these models. This is mainly caused by an overestimation of the cross section for light systems. Furthermore the spectral shape is not described quantitatively, in particular in the low p_t part which is underestimated for all systems. Models which include heavier baryon resonances but not the mean field (RQMD [28], QGSM [29]) predict an increase in the region above the free nucleon–nucleon kinematical limit where multiple collisions become important, in agreement with the observation. At low transverse momenta a large discrepancy between experiment and all models is found. This low-p_t enhancement of pion spectra, now established down to transverse momenta

$p_t = 0$, is still not quantitatively understood in current transport model calculations. At these pion energies a quantal description of meson propagation may be needed and/or medium effects may have to be included as proposed in [30]. It appears that current theoretical treatments are still lacking essential ingredients. Moreover, improved calculations will have to include a proper momentum dependence of pion-absorption and rescattering. Pion absorption requires at least two correlated nucleons and is thus very sensitive to the baryon density and its rapid variation in the expansion phase of the heavy ion collision. A satisfactory understanding of pion spectra will consequently require a simultaneous and consistent description of particle production data as well as nucleon and fragment emission patterns.

In conclusion, a first systematic study of the mass dependence of π^0 production at 1 A GeV projectile energy has been reported. The pion spectra exhibit an increasing concavity with the total mass of the colliding system. The mass dependence of high energy pions shows a deviation from a purely linear behaviour which is attributed to higher-order processes like multiple collisions leading to an increased population of higher baryon resonances. There is no generally accepted explanation for the enhanced π^0-yield at low transverse momenta. None of the presently available theoretical descriptions reproduces the mass dependence of pion production quantitatively, emphasizing the need for more refined calculations.

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